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Characterization of Electronic Displays using Advanced CMOS Single Photon Avalanche Diode Image Sensors

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Abstract

Advanced CMOS Single Photon Avalanche Diode Arrays have the potential to reveal characteristics of electronic display panels that have, until now, been extremely challenging or impossible to measure routinely. We demonstrate the use of a CMOS SPAD array to make optical measurements of pixels of an OLED microdisplay at very high sampling rates, very low light levels and over a very wide dynamic range.

Author Keywords

CMOS Single Photon Avalanche Diode SPAD; OLED Microdisplay; Display measurement; Quanta Image Sensor.

1. Introduction

The Single-Photon Avalanche Diode (SPAD) was first reported by McIntyre in 1960's at RCA [1]. It can be thought of as a solid-state Photo-Multiplier Tube (PMT). SPADs have found many applications due to the combination of their inherent compact and robust nature along with their very fast response, single-photon sensitivity and ability to time-stamp the moment of photon capture. CMOS SPADs opened the door to dense arrays of pixels with local (in-pixel circuitry) plus sophisticated on-chip signal conditioning and processing [2]. Recent applications of SPADs range from time-of-flight 3D vision [3] and fluorescence lifetime imaging microscopy (FLIM) [4] to imaging of ultrafast physical processes like light in flight [5]. With the recent development of SPAD-optimized advanced CMOS processes it is becoming possible to overcome some of the limitations of earlier CMOS-SPAD arrays such as very low Fill-Factor (FF) and implement SPAD high-sensitivity quantum image sensor arrays. In this manuscript, we report on the use of a state-of-the-art CMOS-SPAD Image sensor array to optically characterize a small array of pixels of an electronic display. We demonstrate that the method can measure very high dynamic range and very fast transient optical response. The measurements are carried out on a small array of pixels that are part of an Organic Light Emitting Diode (OLED) microdisplay but we believe that the technique is applicable to a wide range of display and other photonic technologies.

Microdisplays are ultra-miniature display panels designed to be viewed under optical magnification, usually in projection- or near-to-eye-systems. The combination of emissive, fast response and low power consumption makes OLED a favored candidate for microdisplays. However, it is challenging to evaluate the pixel level optical response of OLED microdisplays. OLED microdisplay pixels are extremely small, usually < 10 µm pitch, often with a low total light output per pixel. The optical switching time of an OLED can be << µs [6].

2. Experiment

(a) CMOS SPAD QVGA Sensor

We employed a CMOS SPAD image sensor for our OLED pixel optical measurements. The 320×240 array with 8 µm pixel pitch, 26.8% Fill-Factor (FF) image sensor (labelled SPCImager) was fabricated in the 130 nm Imaging-CMOS process of ST Microelectronics (Fig. 1 (a) [7]). The image sensor can be operated as single-bit digital readout continuously at a rate of several kilo-frames per second (kfps). The SPCImager is used here as a fast Quantum Image Sensor (QIS) in which the number of photons detected is derived from the oversampled photon density.

Fig. 1 (b) shows the experiment setup with Olympus BH-2 Microscope. The SPC Imager is mounted on the microscope camera jack using a custom-designed 3D-printed holder.

(b) OLED Microdisplay Test Pixel Array

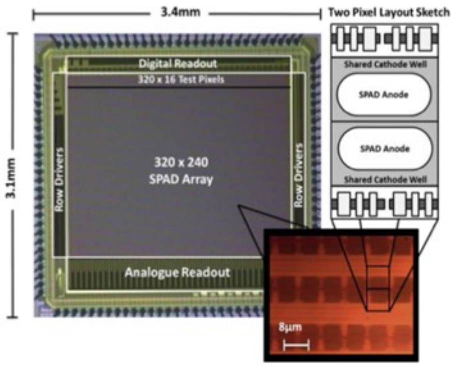
We have implemented several OLED pixel driver circuits in microdisplay test arrays in ST Micro-electronics 130 nm Microdisplay CMOS process [8]. A photomicrograph of a 4×6 test array, with surrounding dummy pixels, is displayed in Fig. 1 (c). These arrays are deposited with tandem OLED stacks. The measurements are mainly taken on two types of those pixel driver circuits, i.e. the source follower pixels and the pulse width modulation (PWM) pixels. The source follower (SF) pixels apply bias voltage on the OLED. Fig. 1 (d) shows the method of generating grayscale for the SF pixels. There are two modes to drive the PWM pixel. It can be operated as an analogue PWM pixel, in-pixel stored voltage is compared with a ramp signal, producing a pulse duration. Or it can be driven as pulse code modulation (PCM) pixel as shown in Fig. 1 (e). The in-pixel memory is effectively a 1-bit DRAM. The OLED anode voltage is switching between VSS (Low) and VDD (High) by comparing the DRAM with a static voltage. The source-follower pixels are 4.7 µm pixel pitch, and the PWM pixels are 5.2 µm pitch.

3. Optical Characterization of OLED microdisplay pixels

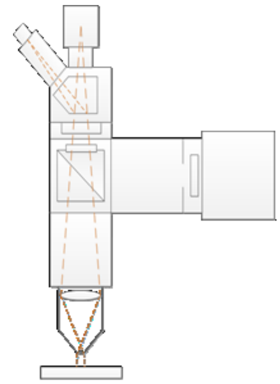
(a) High Dynamic Range Steady State Measurement - Source Follower Pixel

The conventional 2T source-follower pixel schematic is shown in **Error! Reference source not found.** (a). The drive transistor, MN2, is Nbiased as a source-follower. Thus, in the steady state the OLED anode voltage is $V_{Anode} \cong V_{data} - V_{th}$. By sweeping the DATA voltage, the output light level of the OLED can be varied from vary from ~0 photons to >10^3 Cd/m2:

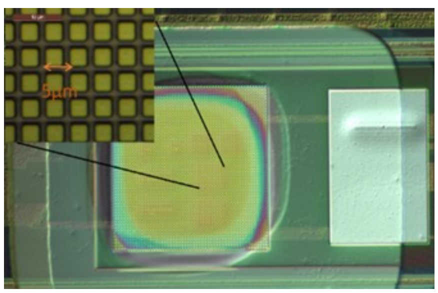
For SPAD QIS cameras, high dynamic range measurements can be realized by spatial and temporal oversampling. The probability of photons arriving at each SPAD pixel follows a Poisson distribution. By temporal and/or spatial oversampling, the arrival rate of photons incident on SPAD pixels can be recovered from analysis using Poisson arrival statistics [9, 10].



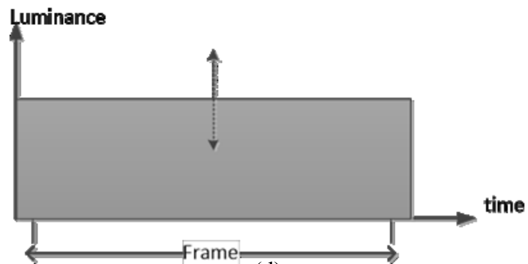
(a)



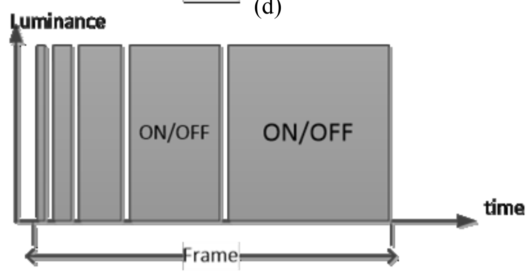
(b)



(c)



(d)



(e)

Figure 1. (a) Photomicrograph of test array. Inset: zoom in layout of the 4×6 array with dummy pixels. (b) Grey scale generation for source follower pixel. (c) Grey scale generation for PCM pixel. (d) Photomicrograph of the SPAD-based QVGA imager [7]. (e) Schematic of the measurement setup based on Olympus BH-2 Microscope.

In capturing the image shown in Fig. 2 (b), each OLED microdisplay pixel is mapped onto approx. 400 (20×20) SPAD pixels. The number of incident photons can be derived from the temporal and spatial average photon rate. Fig. 2 (c) shows the sweep of input DATA voltage versus the incident photon counts and pixel current with different frame time. The incident photon is derived from 1000× temporal oversampling and 400 spatial binning. It can be found that the different exposure time (50 µs, 100 µs) can recover a similar incident photon level.

(b) Fast Transient Measurement – Modelling PCM Pixel Optical Response

Another method of achieving grey scale is Pulse-Coded Modulation (PCM). Viewing imperceptibly-fast binary (ON/OFF) switching of the OLED produces the impression of grey scale at each pixel. The perceived grey scale is, theoretically, proportional to the on/off time ratio of each frame provided the luminance level is constant during each pulse and from pulse to pulse.

For transient measurement, an 8-bit, 100 Hz PCM scheme is applied to the OLED pixel array. The oversampling technique is performed over a period (e.g. the photon counts at t0 are averaged with t0+T, where T is the OLED frame time, say 10 ms). In a similar manner to the steady sate measurement shown in Fig. 2(b), the OLED pixel array is imaged onto the SPCImager. Each OLED pixel is mapped onto approx. 484 (22×22) SPAD pixels. The 50 kHz (10 µs exposure, 10 µs readout) measurement results of 8b'10101010 and 8b'01010101 PCM scheme are shown in Fig. 3 (a). The number of photon counts/pixel/s is reconstructed through oversampling (100× temporal, 484 spatial).

We find that the OLED pixel luminance is not constant during each coded pulse. Overshoot and decay behavior is shown when the pixel is switched ON from OFF. Moreover, the longer the OLED pixel is OFF before it is switched ON, the greater the luminance overshoot. As shown in Fig. 3 (b), the degree of overshoot from the intended PCM waveform rises approximately linearly with the length of time for which the OLED is switched OFF prior to the OFF to ON transition.

4. Impact

We have demonstrated a novel OLED microdisplay optical characterization method with a SPAD image sensor. SPAD image sensors are expected to match or even exceed the performance of sCMOS and EMCCD for very low light molecule identification [11, 12]. The SPAD image sensors are also capable of observing

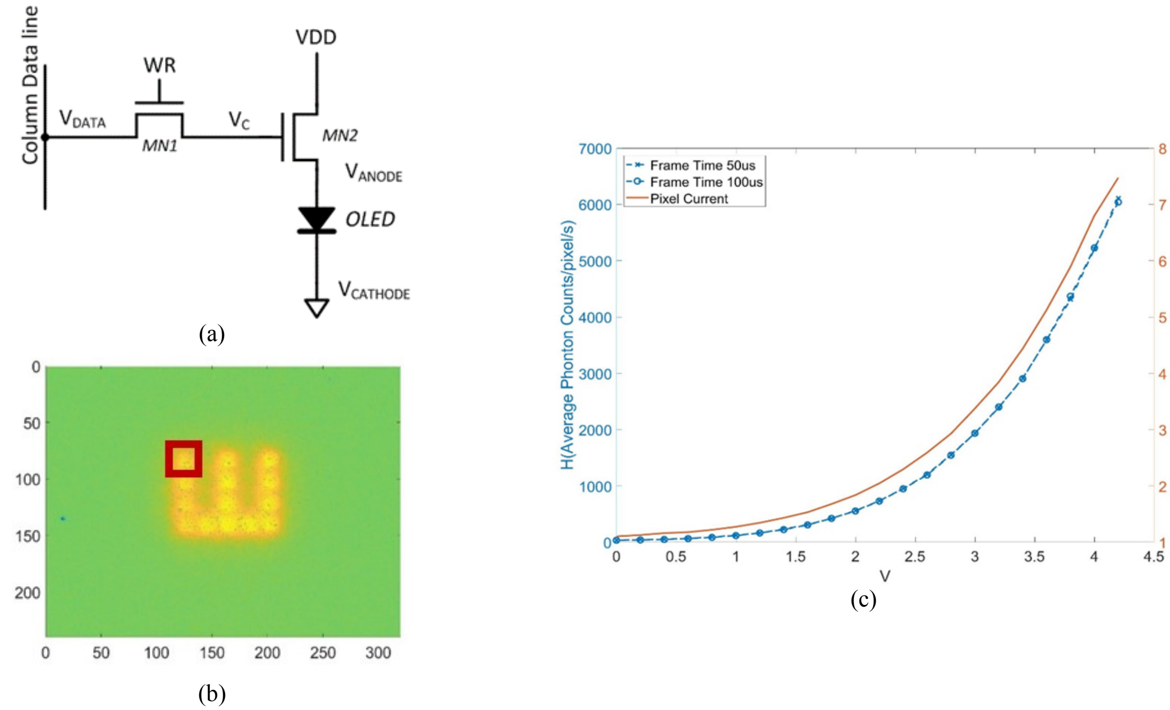


Figure 2. (a) Source follower pixel schematic. (b) SPAD array image of the OLED pixel array (1000 oversampled field). (c) DATA voltage versus Average incident photon rate each SPAD pixel of 1000 oversampled field (left y axis), average OLED pixel current (right y axis).

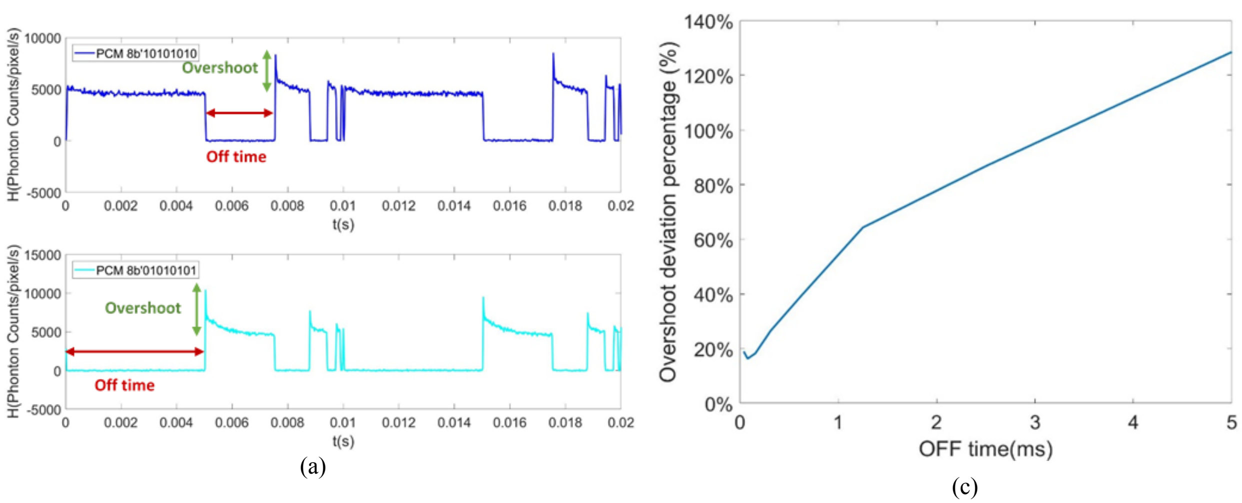


Figure 3. (a) PCM pixel transient measurement of 100 oversampled field, encode 8'b10101010 (blue), and encode 8' b01010101 (orange). (b) Pixel OFF time versus overshoot magnitude.

Table 1. Comparison with existing technology

Measurement system	Image sensor technology	Dynamic range	Minimum Measurement time
SPCImager	SPAD	4 – 10^7 photon counts/s for 100ns exposure, -5C° cooling	5us including readout for 10 rows of SPAD pixels
2-in-1 Imaging Colorimeter [14]	CMOS	0.01 cd/m² – 5000 cd/m²	65 ms at 100 cd/m², 330 ms at 1 cd/m²
MotionMaster [15]	CCD	N/A - Detects motion blur (Image difference)	typ. 0.26 ms – 0.52 ms
NPL PMT spectroradiometer [13]	PMT	10 – 10^7 photon counts/s	NA
GLRT Gray Level Response Time Measurement Kit [16]	PMT	16-bit DATA	40 μs

dynamic behaviors occurring over short-time scales [11] (in the present case, OLED pixel luminance overshoot during switch ON) which is inaccessible to sCMOS sensors. SPCImager can achieve 10^7 photon counts per second for 100ns exposure, and dark count as low as 4 counts/s when cooled for each pixel, similar performance to PMT single-point sensor reported by Fatadin et.al. [13] Table 1 shows an outline comparison of the SPAD-based SPCImager and other state-of-the-art systems. SPCImager measures significantly faster and is capable of nonuniformity measurement as a camera sensor.

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